

Subsidence assessment of New Delhi, India using custom PS-InSAR technique and Multi-sensor InSAR data.

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Abstract

Land subsidence is a significant problem in the developing urban area, which has been reported worldwide. The factor which causes land subsidence is related to over-exploitation of the underground fluid such as water, petroleum, gas, etc. The problem is worse in developing countries where laws regarding groundwater extraction are not strict, and there is poor control of authorities on the extraction process. The area selected in this study is a part of New Delhi, the capital city of India. This area indicates a high rate of urban growth during the past decades. The present research paper focuses on assessing land subsidence using multiple SAR sensor data and exploiting the PS-InSAR technique. The data used for this study are Cosmo-skymed, Sentinel-1A-B, and ALOS PALSAR. These sensors operate in X, C, and L-band, which covers over ten years, from 2007 to 2018. Groundwater level data also collected for the same period, and a level depletion map was generated using the interpolation technique. Monitoring land subsidence with ground-based conventional technology is time-consuming and can be carried out in a limited area due to the financial implication. PS-InSAR is an established method to detect the surface movement using the SAR sensor's time-series data. The result shows that a twenty centimeter of land subsidence is visible in some areas, validated with the collected ground evidence. The affected area is also showing resemblance to the groundwater depleting condition in those areas.

Keywords: Groundwater over-extraction, Land subsidence, New Delhi, PS-InSAR, SAR.

1. Introduction

Land subsidence in the urban region is most often caused by human activities, mainly from subsurface water extraction. The principal causes are aquifer-system compaction, drainage of organic soils, underground mining, hydro-compaction, natural compaction, sinkholes, and thawing permafrost. Any of these conditions can trigger land subsidence, which can be visible on the ground surface. In an urban area, ground subsidence can be seen in building cracks in significant buildings and other concrete structures. Rapid urban development is one of the factors which can trigger land subsidence by affecting the groundwater table and surface/underground excavation. We have seen the fast, deteriorating groundwater table in Delhi region (CGWB reports 2007-18, New Delhi).

SAR interferometry can be used for several land-based applications. Several satellites are orbiting the earth acquiring radar images of the earth's surface, mainly mapping and monitoring the earth's surface. The radar images are capable of penetrating through the cloud coverage and insensitive to weather. These radar images can be acquired in different bands such as X, C, and L bands. There are several different image acquisition geometries also available with varied incidence angle. Different image acquisition modes such as Spotlight, Strip map, TOPSAR (Terrain Observation with Progressive Scans SAR), and ScanSAR (Scanning Synthetic Aperture Radar) are available. Spotlight and strip map modes are used to acquire the high-resolution images, while TOPSAR and ScanSAR modes are used to resolve image acquisition. Images acquired using the different modes can be processed using the dedicated radar image processing techniques. A suitable set of the band, geometry, and incidence angle can be selected for a particular application. C-band data used in this work is acquired in TOPSAR (mode with 29.1 to 46.0-degree incidence angle while the other two datasets are acquired in the X and L bands.

In the radar images phase and the amplitude of the reflected signals are recorded. The same area's repeated images are used to map the topographic changes over two acquisitions in an InSAR image pair. This pair is acquired by the same satellite and sensor. Its mandatory that futrue acquisition is planned in such a way that future image shall also be acquired from the same orbital position or possibly with minimum deviation. This deviation orbital position of the platform is called the baseline. The baseline is essential; while a wider baseline is good for topographic mapping smaller baseline is vital for deformation mapping (Pepe et al. 2017). The data used in this work is having a short baseline, which makes this data very useful in estimating the land deformation. An optimum baseline and a significantly high number of images are essential to achieve a good result for land subsidence monitoring using the PS-InSAR technique (Malik et al. 2019).

Several satellites are orbiting the earth acquiring radar images of the earth's surface, mainly for surface mapping. Radar images are captured by a synthetic aperture radar (SAR). SAR can be mounted on a moving platform, such as unmanned aerial vehicles (UAV), aircraft, or space-borne platforms like a satellite. The SAR system has its origins in an advanced form of side-looking airborne radar (SLAR). Side-looking airborne radar (SLAR) is an aircraft or satellite - mounted imaging radar pointing perpendicular to the direction of flight. A non-perpendicular (squinted) mode is also possible. SLAR can also be fitted with an antenna, a standard antenna, or an antenna using a synthetic aperture.

The radar images are capable of penetrating through the cloud coverage and insensitive to weather. This feature provides the upper hand to this technology over the passive remote sensing data. SAR sensors can acquire the radar image day and night. The phase and the amplitude of the reflected signals are recorded. Repeated images of the same area are used to map the topographic changes over two acquisitions. Using a set of images acquired over the same area for an extended period is used for time series analysis. This technique helps to estimate the slightest change in the surface over the period of available data. The phase difference between these SAR images can be determined to calculate displacement (Colesanti et al. 2003). The equation (1) shows the representation of the interferometric phase $\Delta\varphi_{int}$. (Hooper et al. 2004).

$$\Delta\varphi_{\mathrm{int}} = \Delta\varphi_{\mathrm{topo}} + \Delta\varphi_{\mathrm{displ}} + \Delta\varphi_{\mathrm{atmo}} + \Delta\varphi_{\mathrm{noise}} \quad (1)$$

($\Delta\varphi_{topo}$ = Residual topographic height, $\Delta\varphi_{displ}$ = estimated displacement,

$\Delta\varphi_{atmo}$ = atmospheric phase disturbance, $\Delta\varphi_{noise}$= non-removable phase disturbance.)

Mapping of the land subsidence with high precision can be achieved using the differential InSAR technique (D-InSAR) (Strozzi and Wegmuller 1999), which measures ground displacement in the radar line-of-sight (LOS) direction of a satellite by computing the phase difference of two temporally separated SAR images (Gabriel et al., 1989; Massonnet et al., 1993).

Time-dependent subsidence monitoring traditionally relies on time-series techniques, such as persistent scatterer interferometry (PSI) (Kampes, 2005; Cigna et al. 2011; Bock et al. 2012; Monika et al. 2018 and 2020) and small baseline (SB) interferometry (Berardino et al. 2002). Partially Coherent Targets-based deformation estimation is helpful to process the data with low coherence. (Perissin and Wang, 2012).

A small baseline interferometry technique has proven its importance in estimating the deformation using the narrow baseline InSAR data. (Perissin and Wang, 2011). The least Square database approach is also demonstrated in estimating the deformation using the InSAR data. (Usai 2003). A new addition of the SqueeSAR technique is recently even invented to monitor the deformation in low coherent areas. (Ferretti et al., 2011). A combination of the two different PSI and Small Baseline Subset (SBAS) techniques employed to produce the best possible estimation of ground deformation. (Yan et al. 2012). Since the study area is an urban site, there was a sufficient PS in SBAS and PSI processing.

Each technique is best matched to a particular set of conditions. PSI enables precise characterization of linear deformation affecting "persistent scatterers" abundant in urban areas (Perissin et Al. 2012; Bürgmann et al. 2006). Subsidence is a global problem. Lots of studies have been undertaken in various cities globally, such as Mexico (Du. 2019), Shanghai (Perissin et al. 2012), many cities in Indonesia (Abidin et al. 2011), and Vietnam (Ho Tong Minh et al. 2019). In the current study, we have targeted NCR, New Delhi, India, to assess land subsidence induced due to increased urbanization. The result generated from SAR data validated using the ground table data from 2007 to 2018. It is evident that in some parts of the National Capital Region (NCR), there is a sharp decline in the groundwater table, especially the region which is undergoing rapid urban development. In this study, the result generated using the multiple sensors present the same trend, and it shows a complete long-term time series starting from 2007 to 2018.

2. Study Area

Delhi, the capital of India, is a densely populated metro city in India. Lots of construction activities leading to urbanization have taken place in the NCR, Delhi. Figure 1 shows the study area's screen capture, the study area's map, and its location on India's map. The study area is selected as the New Delhi area is chosen for the study as this is the capital region of India and has great importance. Several large infrastructure projects are located in the study area, worth being monitored for any possible land subsidence. In addition to this, the availability of the data of different study areas was the reason for the section of the study area. Figure 2 shows the footprint of the different sensor datasets listed in the legend using a different color. Overlapping of the footprint confirms the very good amount of common area is available of the data for comparison. The total area is around 1600 km^2 (40 km x 40 km), while New Delhi is in the center. Here in the next section, more information about the area is presented.

2.1. Geology

It is very well known that the rock of the area belongs to the oldest geological era as some of the regions belong to the Aravali range. Also, many rocks belong to the latest time period as categorized by the geologist. The rock belongs to the Pre-cambrian period and belongs to the Alwar series of the Delhi Super Group (system). The Geology of Delhi NCT is depicted in figure 3 (Kual and Pandit 2004; Bansal et al. 2009). The tectonics of the area is quite complicated as many ridges and faults neighbor it. The alluvium lies over these rocks and is classified as older (also known in India as *Bhangar*) and younger alluvium (also known as *Khaddar*). Logically the younger alluvium is found near the river in its flood plains.

2.2. Geomorphology

The main Geomorphic features of NCT Delhi, as observed by the Geological Survey of India, are reproduced as Geomorphology Map in figure-4. Dissected hills with rocky surfaces are the oldest features. The Delhi Ridge is a part of the Aravalli Range trending in SSW- NNE direction, occupies the south-central region of the NCT of Delhi. This Ridge extends up to the western bank of Yamuna River near Okhla in the south. In the northeast direction, it extends till the Wazirabad. The Aravali Ridge consists of quartzite rocks and acts as the natural watershed of the region. This Ridge acts as a groundwater divide or curtain between the West and East Delhi. Many small watersheds originate from this Ridge. As per the NAQUIM report (2016), these geomorphic features can be grouped into three broad heads:-

(i) Flood Plains of Yamuna River,
(ii) Older Alluvium Plains,
(iii) Rocky surface

The younger flood plains of Yamuna are low-lying areas along the river in the eastern, north-eastern, and the northern part of Delhi.

The older plain surrounds the Ridge and the hillocks and has very gentle undulations. Again it can be further sub-divided into the following depending on the known localities: -

- Plains of Najafgarh (occupies the western and southwestern part of the area and indicated by landcover of sandy dunes and other sandy features).
- Delhi Older Alluvium Plain (it has a gentle slope and is on the eastern side of the Ridge).
- Plains of Maidan Garhi (it is relatively higher than others).

The rocky surface consists of isolated hillocks and linear ridges, which are structurally controlled. These are made up of the rock of the Delhi Subgroup. One such famous hillock is the Raisina Hill, which holds many buildings that house many important offices of the Government of India. The maximum elevation among these hillocks is 362 m above the mean sea level.

Figure 5 shows the cross-section showing the study area's lithology (Central Ground Water Board, Delhi, India booklet 2013). In this figure, several different litho-stratigraphic units are visible.

Geological cross-sections one (top) is along Kair to Nicholson Range, and the second (bottom) is along Kair – Dwarka – R.K. Puram are presented in figure 5. A very thick pile of alluvium spread over the top of the basement rock, and it also has alternate layers of clay, silt, sand, and pebbles. In 1st 50m of depth, close to fine to medium sand with silt grade sediments frequently appears along with light brownish yellow coloured clayey bed mixed with uneven pebbles. While after the depth of 50 m, the thickness of the silty layer –clay and light-yellow clay beds with pebbles increases. Further to 80m, the semi-plastic and plastic clay beds are also common.

3. Data used

Table -1 shows a summary of the data used. In this study, a total of two hundred thirteen (213) images have been used from different sensors. Figure 2 shows the coverage of the different datasets over the study area. All the different sensor has different characteristic and different data collection parameter. It leads to the different data collection extent on the ground. Eighteen images of ALSO PALSAR are used, which cover close to four years starting from January 2007 to January 2011. HH polarization of ALOS PALSAR data is used. In this stack, the average spatial baseline was above eight hundred meters, which was higher than other data used. The graph of baseline distribution in this image series is shown in figure-3. In this paper, forty-five images with HH polarization from the COSMO-skymed mission were used, which cover over six years starting from June 2011 to January 2018. The average spatial baseline in this stack was above four hundred meters. A detailed graph showing spatial and temporal baseline distribution with the selected master is shown in figure 6. We have also attached a table on the supplementary material depicting the data used of the different sensors.

A total of one hundred and fifty images of Sentinel-1A were used in which 77 images were acquired in descending mode, and 73 images were acquired in ascending mode. Sentinel-1A image covers over four years, combined both modes. In both the Sentinel-1A images stack, the average spatial baseline was slightly higher than 30 meters. In the figure-3 a different graph shows the spatial and temporal baseline distribution of data used. Sentinel-1A (Sentinel, 2016), launched on 3 April 2014, operates in four image modes with different resolution and coverage: Strip Map (SM), Interferometric Wide Swath (IWS), Extra Wide Swath (EWS), and Wave (WV) modes. During these modes, both the IWS and EWS modes employ the novel Terrain Observation with Progressive Scans (TOPS) acquisition mode (Torres et al., 2012). With the TOPSAR technique, in addition to steering the beam in range as in ScanSAR, the beam is electronically steered from backward to forward in the azimuth direction for each burst, avoiding scalloping and resulting inhomogeneous image quality throughout the swath (De Zan et al., 2006). Figure 6 shows an overview of perpendicular and temporal baseline distribution concerning the master and slave members in all the datasets used in this study.

We have also collected the groundwater data for the study period. This data has been acquired using the borehole in four different seasons, such as January, May, August, and November. May month data served as the pre-monsoon, during August as the post-monsoon data. We were able to locate some points in the area where we found the subsidence. This helped us to present a fair comparison between the groundwater depletion conditions with respect to subsidence.

4. Data Processing

This section has been segregated into three sections to address the different sensor data processing. Data processing details have been divided into three sections: for Sentinel-1, and two is for Cosmo-skymed, and section three is for ALOS PALSAR data processing. It's worth mentioning here that Sentinel-1 data is captured in TOPS mode, which is quite different from Stipmap mode in which Cosmo-skymed and ALOS PALSAR data is acquired. The PS-InSAR processing required significant hardware resources (Jacinth Jennifer Jesudasan et al., 2020), so a high-end workstation was used to carry out processing work. All the data processing chain includes the steps for atmospheric Phase Screen (APS) as this is important to take care of the error introduced by the atmosphere in the SAR time series data. (Tang et al., 2016). Sarproz software (Perissin et al., 2011) has been used for the processing of data.

4.1. Sentinel-1 Data processing

The flow chart for the processing of the Sentinel-1 data (Qin and Perissin, 2016) is shown below in figure 7.

All the images were imported into the data processing environment, and all the terrain observation by progressive scan (TOPS) processing has been performed. The data used in this study consist of the level one Interferometric wide swath (IW) Single Look Complex (SLC) data subset of 1600 km2. TOPS has their distinctive characteristic, so a standard procedure is required to prepare interferograms of TOPS pairs, which is different from the process used in Stripmap. In TOPS processing, some steps are needed by TOPS. TOPS data is acquired by the backward-to-forward steering of the antenna in the azimuth direction. An additional quadratic phase term in azimuth direction is added due to the steering antenna. Now a step de-ramping is used to remove this quadratic azimuth ramp. During the process, it estimates and removes the quadratic ramp of the image before co-registration. Once data is co-registered, an interferogram is generated. This is a well-known fact that the accuracy of 1/1000 pixels of co-registration is required to ignore the phase ramp introduced by these quadratic terms (Prats et al., 2012). Now to achieve this standard of high accuracy, a general sub-pixel co-registration method will be required. This step is generally followed after the initial coarse co-registration that is used for the case of Stripmap. The subpixel co-registration is usually achieved by the spectral diversity method that utilizes the overlapping parts between successive bursts. Now necessary processing steps for generating interferograms are identical to Stripmap processing.

Figure 7 shows the standard processing chain for importing, de-ramping, and co-registering TOPS data. External DEM from SRTM (Jarvis et al., 2008) has been used for reference purposes. We used around eight thousand points for co-registration. After successful co-registering, all the images with the selected master, interferogram was generated for visual inspection. The part of the interferogram is shown in the figure-8 along with the interferogram from other sensors. All three dataset shows the same trend in the most affected subsidence area.

The next step Persistent Scatter (PS) processing, was carried out. The suitable persistent scatters (PS) were selected based on the amplitude stability index calculated as per equation (2).

$$\boldsymbol{D_A = 1 - m_A . \sigma_A} \tag{2}$$

Where m_A and σ_A are the mean and the standard deviation of the amplitude values

We used 0.7 as a threshold to select the PS, and using this, we could choose about one million PS in our study area. We performed the estimation of the Atmospheric Phase Screen (APS), and after applying APS, the overall coherence of the PS has been improved. Now on these refined PS, we carried out the velocity estimation processing. The final result is again fine-tuned using the temporal coherence as a threshold to remove the low coherent PS, and after that, displacement map is obtained as shown in figure 13 for sentinel-1ascending and descending and other datasets. All the measurement for displacement in InSAR is in line of sight (LOS). Equation (1) shows how the interferometric phase can estimate the line of sight displacement.

4.2. Cosmo-skymed data processing

Now for the processing of forty-five Cosmo-skymed images, the following flow chart has been used. (Kapil et al., 2019). These data series start from the image acquired on 08/06/2011 and end at the image acquired on 02/01/2018. The image obtained on 23/09/2015 was selected as the master to perform the co-registration of the complete stack. An appropriate master image was chosen after considering the temporal and spatial baseline. Extreme weather conditions such as rainfall and snowfall are also taken into consideration for master selection.

Appropriate PS points were selected based on the amplitude stability index as per equation (2). PS point, which has the value above 7, were selected, and a total of 284934 PS could be chosen. After the PS selection, Atmospheric Phase Screen (APS) is estimated using the inverted residual model. Figure-9 shows the processing strategy adopted for Cosmo-skymed data processing.

4.3. ALOS PALSAR data processing

In this study, 18 scenes of ALSO PALSAR data were used as the first image acquired on 19/01/2007 and the last image on the series obtained on 20/01/2011. Image acquired on 04/03/2010 were selected and used for co-registration of the stack. Optimum spatial and temporal baseline were considered while selecting the master and environmental conditions were also kept into consideration. After completing the co-registration, PS were chosen based on the Amplitude Stability index (Equation-2) using a threshold of greater than 0.74, and a total of 54,725 PS were selected. Using these PS, APS estimation was performed and subsequently removed. The final velocity is calculated, and the output was geocoded after further refining the PS point based on temporal coherence. The complete flow chart is shown in figure-9, which is similar to Cosmo-skymed.

5. Results and Discussion

Since the temporal gap was significantly less, all the images were co-registered very well using a very high number of tie points. As a measure of quality checks, some to interferogram generated and verified. Goldstein filters were employed for filtering the interferogram. We were able to produce a good quality interferogram since we had an excellent spatial and temporal baseline. The comparison of the interferogram from different sensors is shown in the figure-6—the impact of the subsidence visible in all the interferograms. Cosmo-skymed is a smaller wavelength, so the number of fringes is high while the ALOS has the longest wavelength. The number of fringes is the least.

In Cosmo-skymed, one fringe is equal to 1.65 cm (half of the wavelength); in Sentinel-1, one fringe is equal to 2.6 cm while the same is 11.6 cm in ALOS PALSAR data (Bert M. Kampes, 2006).

Due to the ideal baseline, we could also achieve a high-value coherence map. Since the quality of the data was excellent, we were able to identify an average of ~40 PS per km2 area in both modes of Sentinel-1 and ALOS data, while 170 PS per km2 in Cosmo-skymed. Most of the PS points fall in the urban area, which is our main focus of this study. The same set of processing was carried out on both ascending and descending datasets of Sentinel-1.

During further investigations, it has been revealed that there are few hot spot sites, which is also confirmed in the interferogram (Figure 8). These relatively faster-moving sites show a very high subsidence rate in the line of sight, while several other areas show a moderate velocity over the time period. These two sites are highlighted in all the sets of interferograms generated using the different sensor datasets. (Figure 8).

Figure 8 shows the complete study area where several land subsidence zones are visible. The two locations, namely A1 in circle and A2 in rectangular, also showing a precise movement in the interferogram. A1 has an area extent around 2.5 x 2.5 km^2 while A2 is smaller than A1. In both locations, we have recorded a high rate of subsidence. Some of the buildings have also been affected in the area. A comparison of the borewell data is also carried out with the time-series data of the selected PS in this highlighted area. Here we could find five borewell point which has data recorded from 2007 to 2018. In this data series, the missing value was replaced by the average value to make a continuous graph for analysis. ALOS PALSAR (figure 9) data point time series also used to create a valid comparison from 2007 to 2011, while the rest of the timeline was covered by the Cosmo-skymed data (figure 10).

As revealed in figure 10, the two locations, namely A1 and A2, also showing a precise movement in the interferogram. A1 has an area extent around 2.5 x 2.5 km^2 while A2 is smaller than A1. In both locations, we have recorded a high rate of subsidence. Some of the buildings have also been affected in the area.

Site A1: This area is marked in a circle in figure 10. This is the most affected site and shows the highest rate of subsidence. This area is approximately 3 km x 2 km and densely populated. This area has rapid building development and dense construction of buildings. The site also records a severe depletion in the groundwater table.

Site A2: This area is marked in a rectangle in figure 10. This is approximately 2 x 1.5 km^2 area showing clear fringes. Plenty of significant construction activities are going on in this area, which seems to be the leading cause of such rapid subsidence. A downfall in the groundwater condition is also noted in this area.

The result generated for 2007 to 2018 entire area in the eastern part of Delhi and adjacent region showing mild land subsidence. This is the same area that has shown a significant amount of development during this frame. In this, lots of new construction activities are taking place, and rapid urbanization has taken place. Figure 13 shows the land subsidence map generated using the X, C, and L band InSAR data using the PS-InSAR technique.

5.1. Water Pumping

This area has too many bore well pumping sets. Each plot has at least one pumping set, and a few of these plots have more than one pump or roughly at least one water pump at every 5 -8-meter distance. The residents have confirmed regarding the water level dropping somewhere around 2-3 meters per year. The same has been established in the CGWB report (2014, 15, 16). Severe water scarcity and associated crisis get reported in the newspaper, highlighting the issue. This area is a hot spot of rapid growth and regularly increased water demand. The authorities have very loose control over the extraction process. The regulations and laws are also not strict about the boring tube wells earlier, which has intensified the situation.

5.2. Groundwater level

The continuous groundwater depletion in Delhi is a significant problem (Singh, A.K., et al.). CSIR report (CSIR News Bulletin 21st to 30 June 2019) also confirms the groundwater depletion in Delhi. In the presented result, it's confirmed that the area under severe groundwater depletion is also showing deformation on the surface. In this study, long-term groundwater level data, which cover the period of 11 years between 2007 to 2018, is used to compare the result obtained from the InSAR data as many as five borewell points located in Shekhawati Line (SW), Kabul Line (KB), Mayapuri (MP), Najafgarh (NG), and Vikaspuri (VP) area were selected surrounding the site where we observed the subsidence. The data of these locations plotted in figure 9, and 10 shows the comparison of the groundwater level data obtained from the bore well with the subsidence. In figure 11, ALOS PALSAR data cover the 2007 to 2011 timeline compared with groundwater data, and it appears to be matching with the rate of subsidence. In figure 12, Cosmo-skymed InSAR data is compared with the respective groundwater data. The trend of both estimated velocity and ground depletion is very much in agreement with both the sensor data.

5.3. Geology

No geomorphological feature could be seen nearby, and the closest fault is around 10 km away from the study area. Two different lithological cross-sections of the study area, one that passes through the site (Figure 5 (1st figure), show that this area has sand as the top layer up to 10 meters deep in the entire area 30-meter sand layer at the site of subsidence. After that, there is a thin bed of clay in the whole of the study area.

In figure 5 (2nd figure), the section passes close to site A1 and has very uniform properties, and this area does not report any subsidence in our result. In this section, we could see a thin top layer of the sand, followed by a clay layer, and we can also see more clay and sand alternatively. This area is very much stable and has no sign of land subsidence, which is also confirmed by our result. It can be concluded that the subsidence is triggered by over-exploitation of groundwater, which is being carried forward by the sandy block due to the non-availability of the recharge.

A geology map of the area is used. We have also used the geological map of the area (CGWB booklet 2013). This cross-section in the below figure three showing the lithology of the study area. It's evident that there are multiple layers of sand, and all the aquifer are recharging since there is no hard bedrock to block them.

5.4. Unplanned urbanization

We also include unplanned urbanization as the cause of subsidence in the study area. In the last two-decade Delhi NCR has shown rapid urbanization. A significant amount of change in urban development has been observed (Tripathy and Kumar, 2019). Our study shows that the area which has witnessed rapid and unplanned urbanization has offered the land subsidence. This area has almost no open space, densely populated, and at some places, we saw the water logging during the rainy season. All this also accelerates the process of subsidence.

6. Conclusion

In the above study, it is confirmed that InSAR data, especially Sentinel-1 TOPS interferometry, can provide excellent results for urban subsidence mapping. Sentinel-1 is open access data that is available to use for anyone. InSAR can give good quality interferogram. Using these interferograms, one can successfully identify the site to an extent, showing the faster subsidence rate. This subsidence appeared to be induced by the over-extraction of groundwater in the given geologic condition, which has triggered the aquifer's consolidation. Other factors that we investigated do not show any relevance with the subsidence. Such a rate of subsidence can damage the building and other big infrastructure projects in the locality. We have also identified the area which is showing a low rate of subsidence as of now. These areas may develop subsidence at a faster pace in the coming years. It gives enough information to look into the subsidence cause and promptly measure a more sustainable and safe future. The policymakers, administrative authorities, urban planners, and civil society can use these results and implement regulations and other checks to mitigate the subsidence problem.

Acknowledgment

The author is thankful to European Space Agency for providing the Cosmo-skymed data via project title "**Land subsidence monitoring in the Delhi/National Capital Region area using Cosmo-skymed interferometry data**" and project ID 33638. Sentinel-1 and ALOS PALSAR data were downloaded from the Alaska Satellite Facility.

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Figure-3

Click here to access/download;Figure;Figure3.png

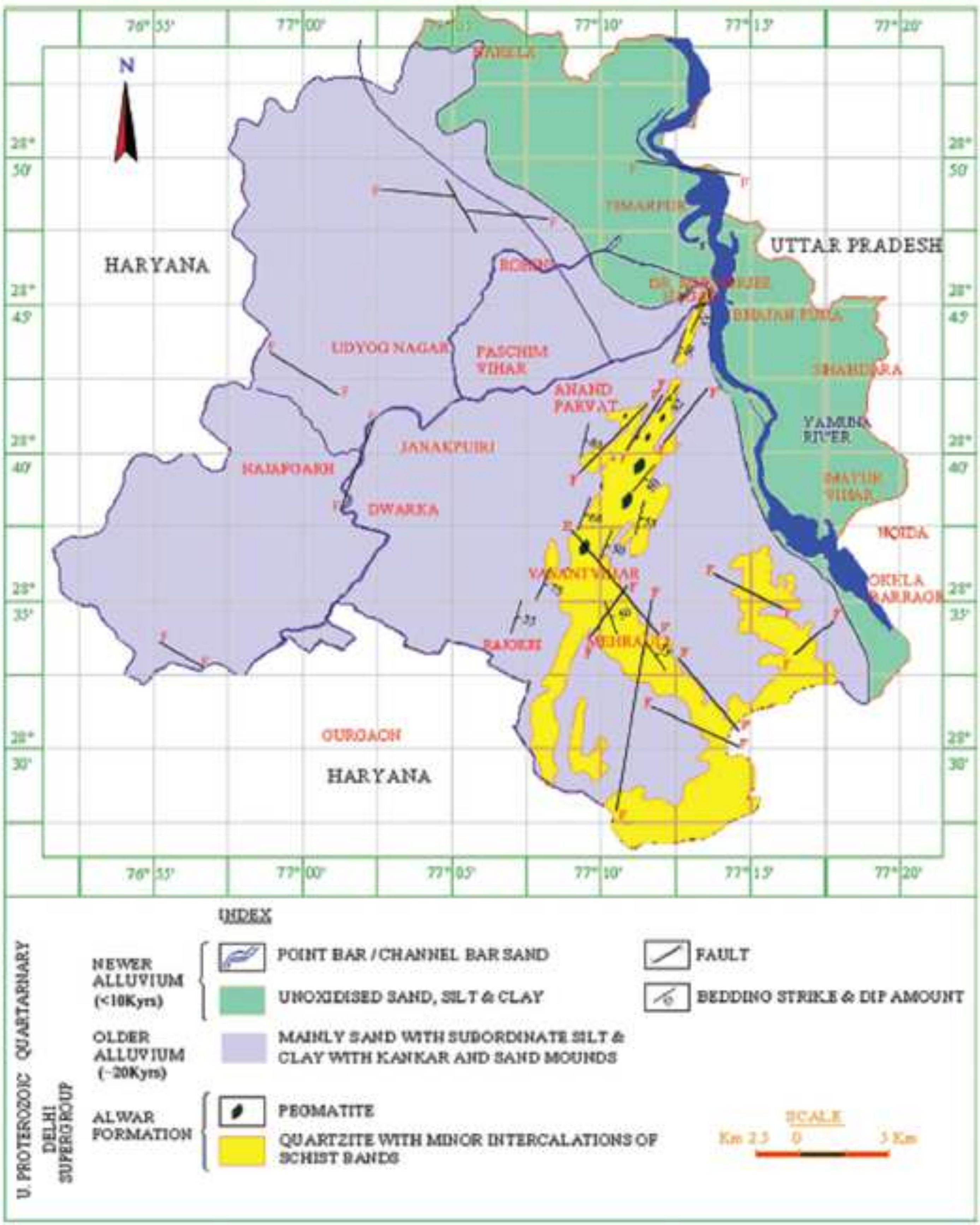

Figure-4

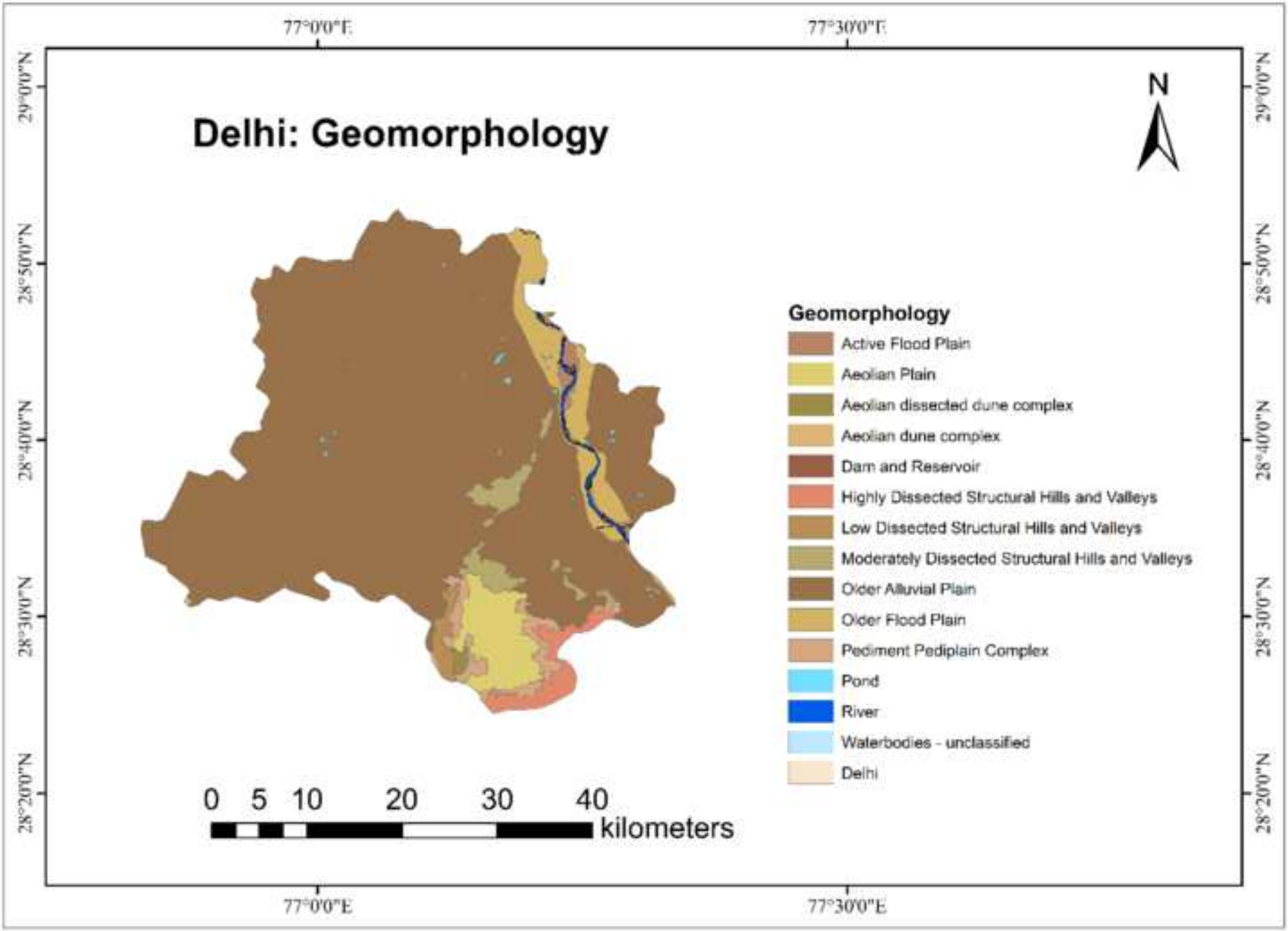
77°0'0"E
77°30'0"E
29°0'0"N
28°50'0"N
28°40'0"N
28°30'0"N
28°20'0"N
Delhi: Geomorphology
N
Geomorphology
Active Flood Plain
Aeolian Plain
Aeolian dissected dune complex
Aeolian dune complex
Dam and Reservoir
Highly Dissected Structural Hills and Valleys
Low Dissected Structural Hills and Valleys
Moderately Dissected Structural Hills and Valleys
Older Alluvial Plain
Older Flood Plain
Pediment Pediplain Complex
Pond
River
Waterbodies - unclassified
Delhi
0 5 10 20 30 40
kilometers

Figure-5

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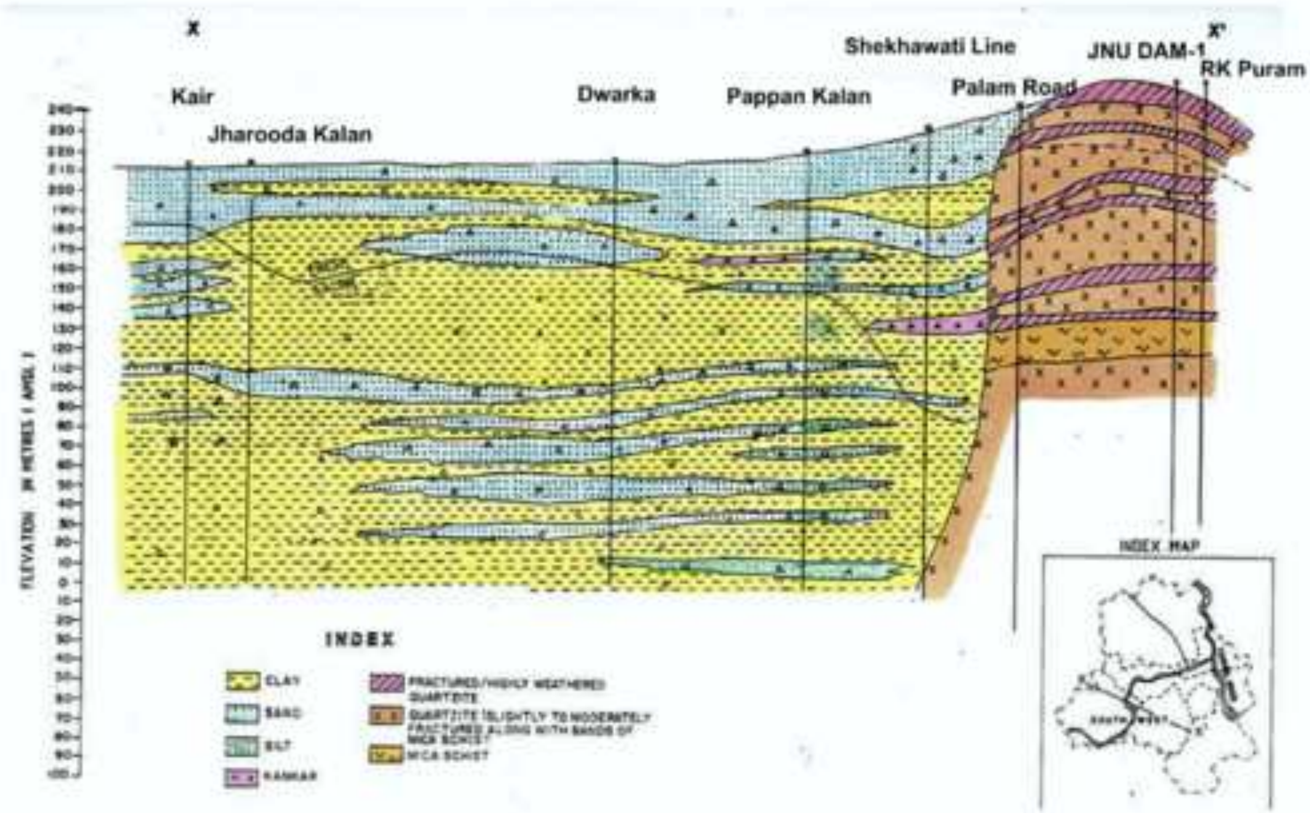

Plate 2 : Subsurface geological cross sections of South West District

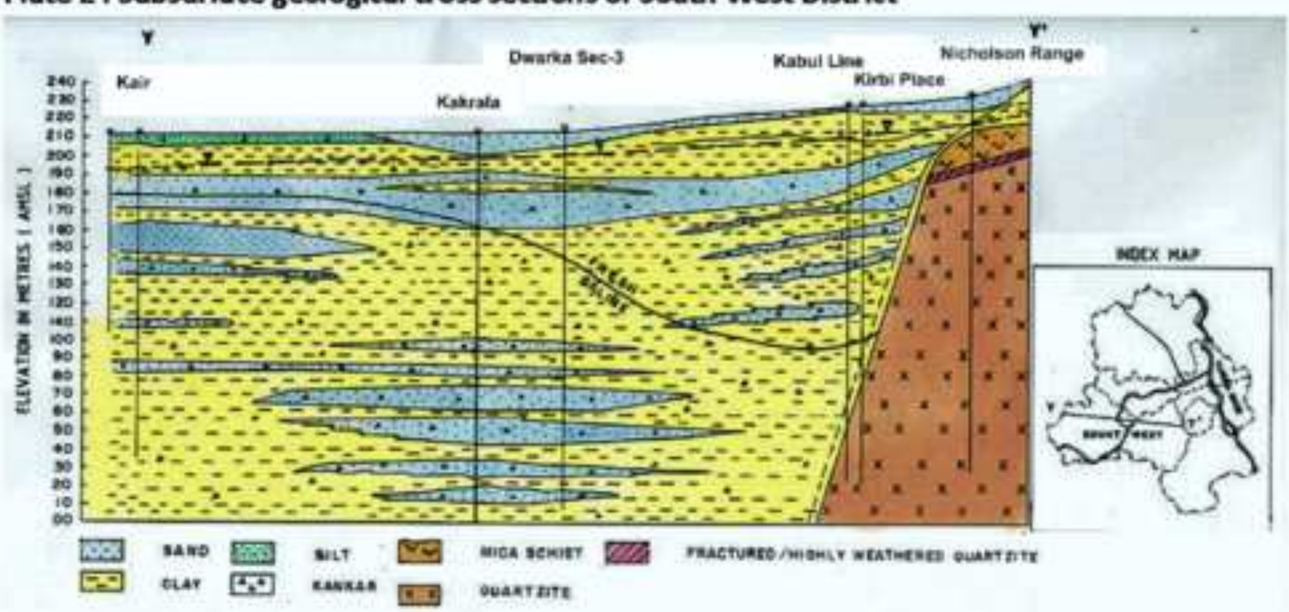

Figure-6

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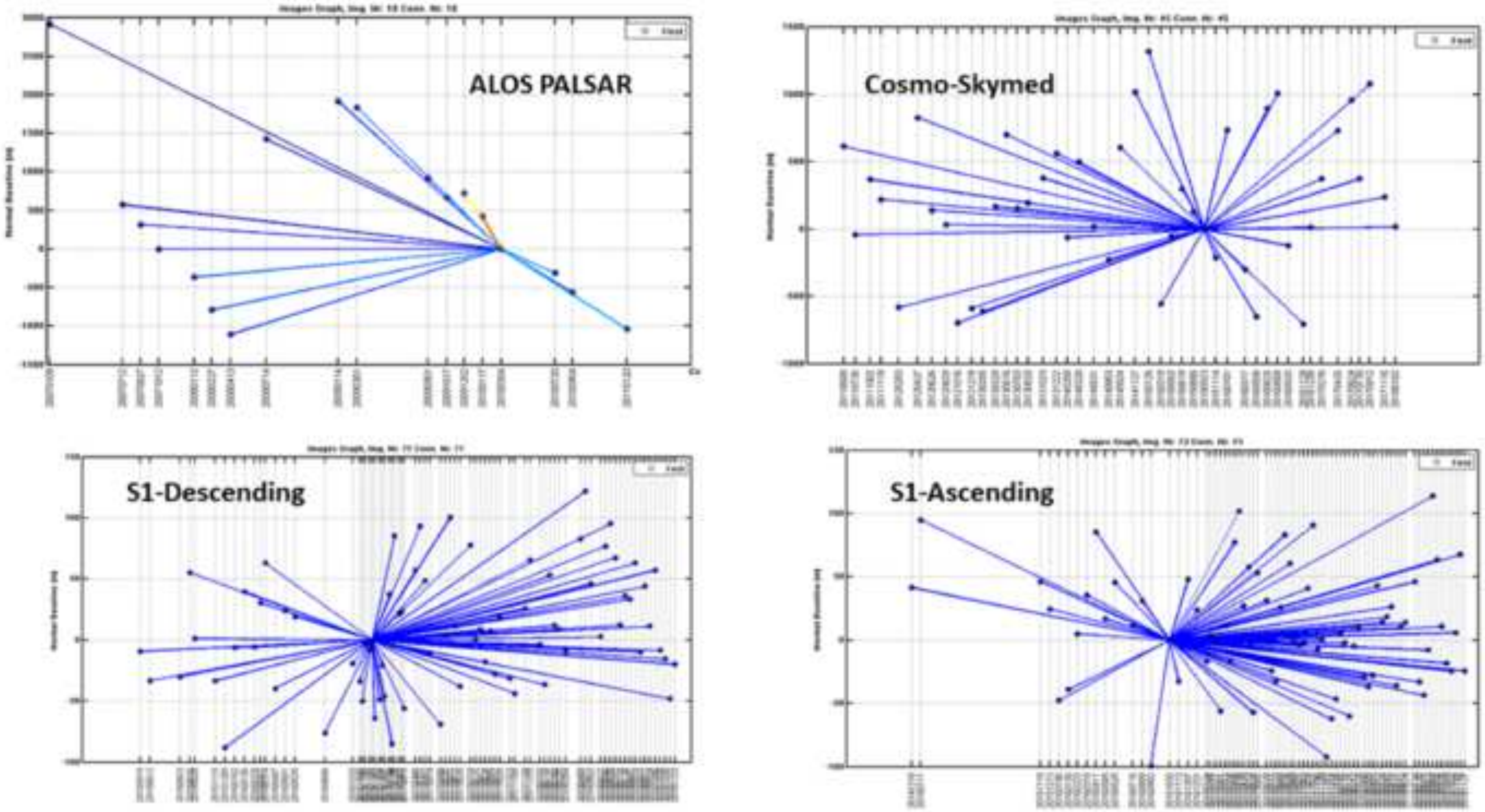

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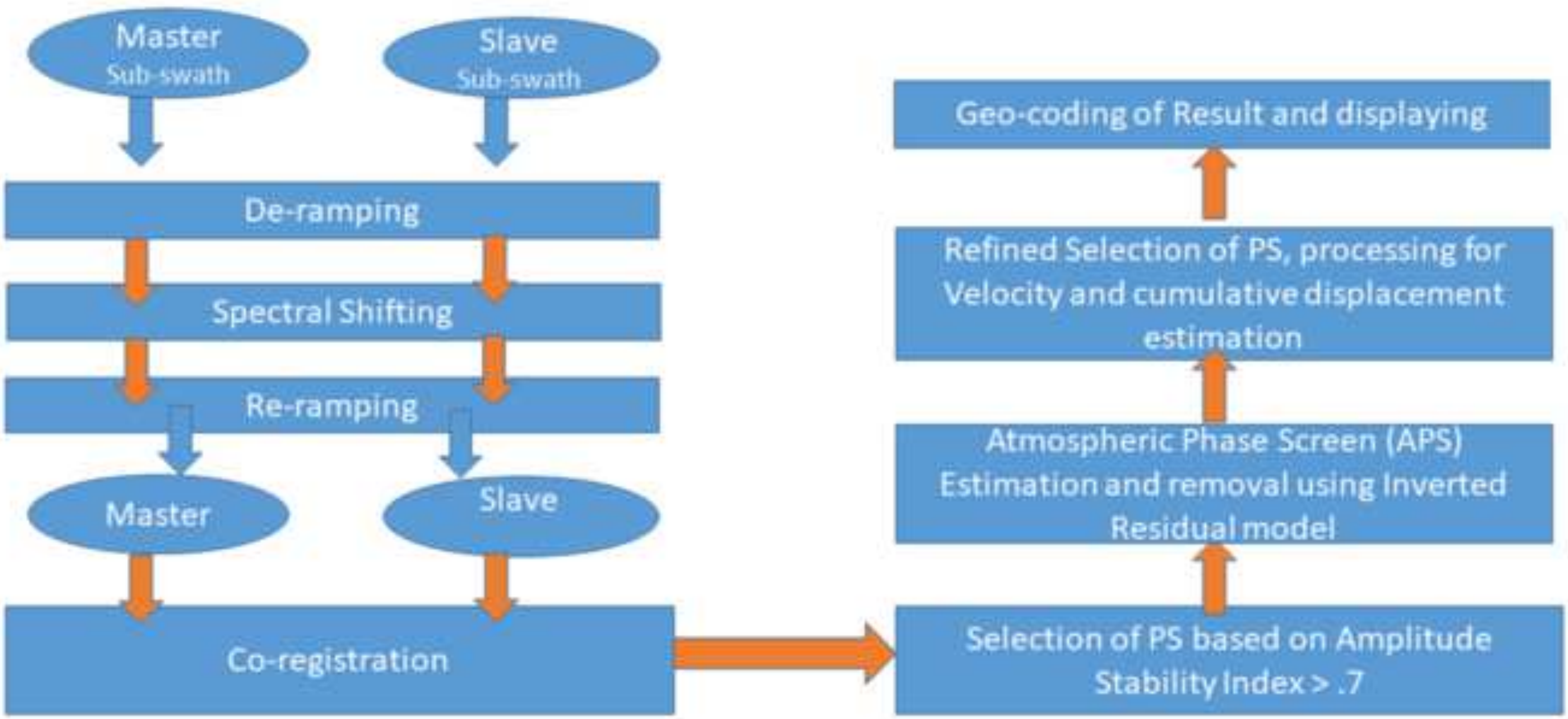

Figure-8

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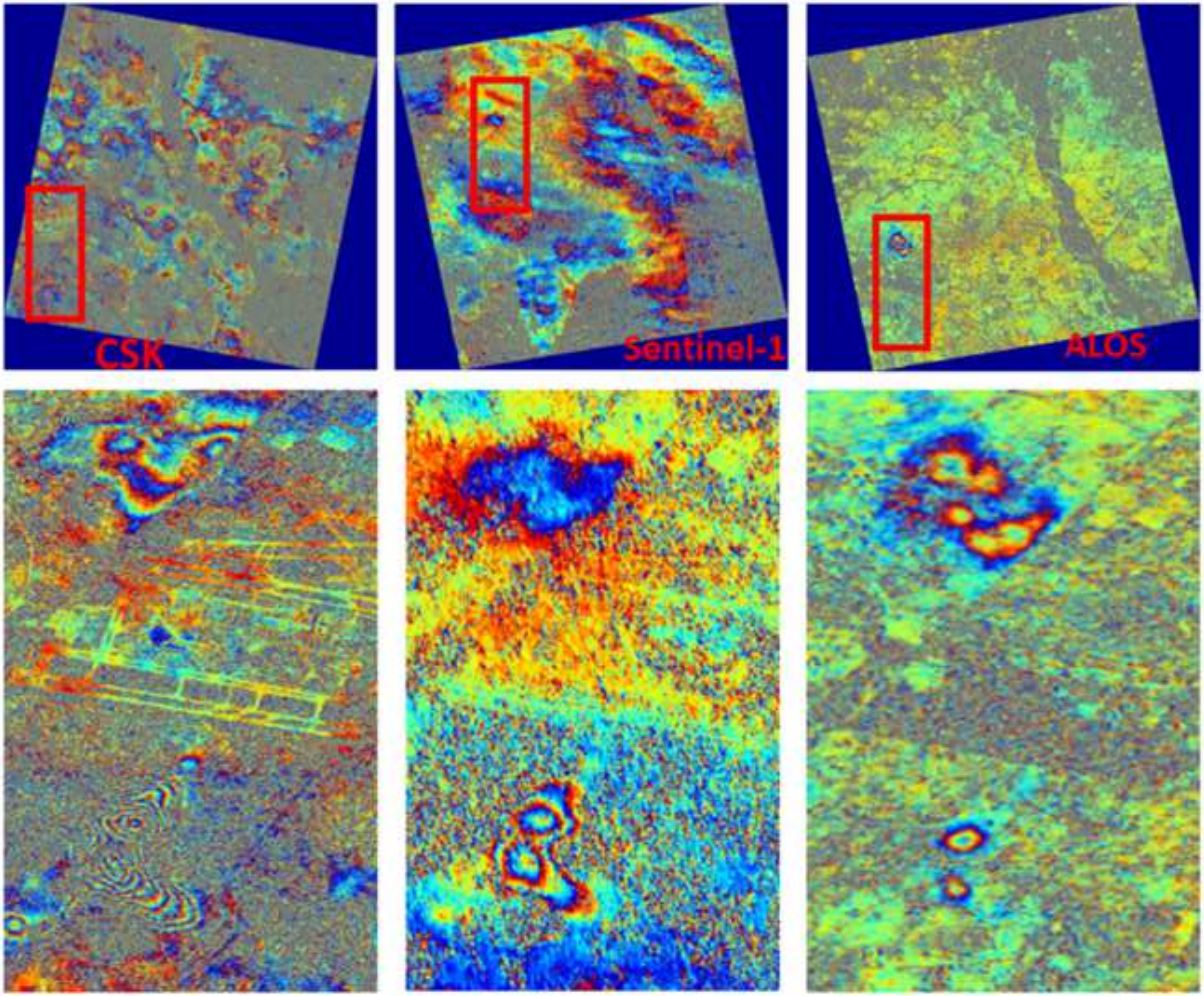
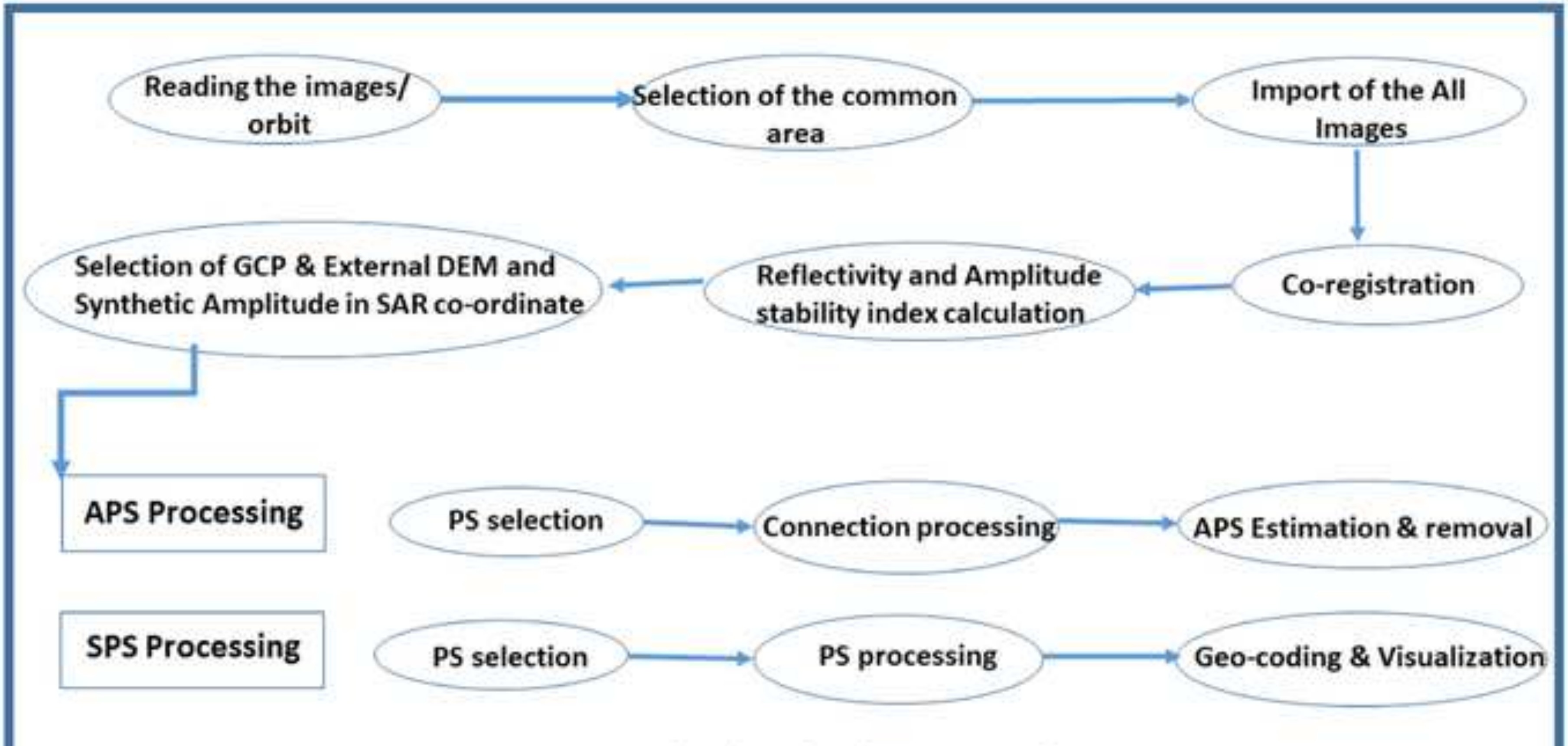


Figure-9

Click here to access/download;Figure;Figure-9.jpg



PS-InSAR Processing Flow chart in SARporz software

Figure-10

Click here to access/download;Figure;Figure-10.tif

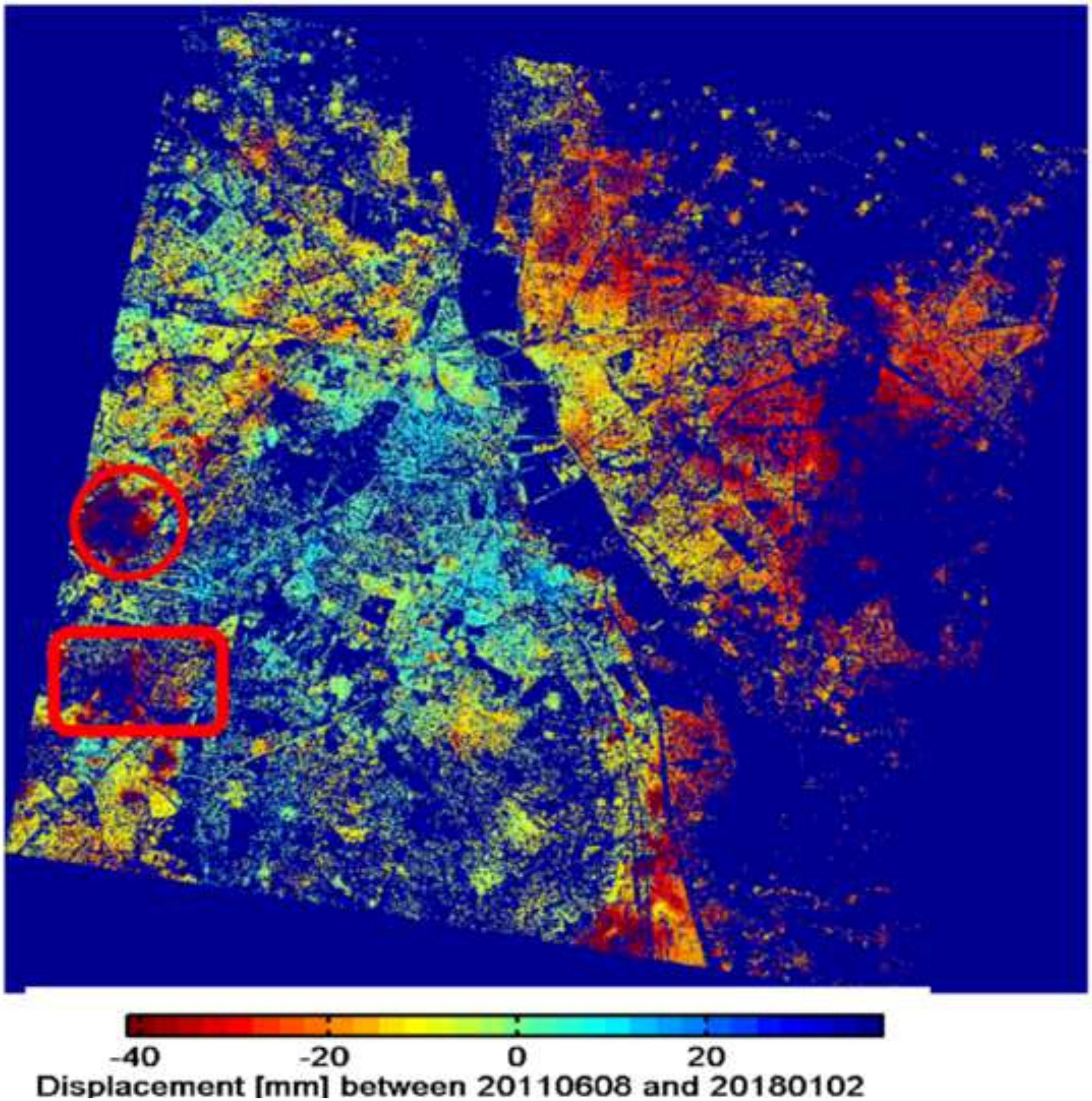


Figure-11

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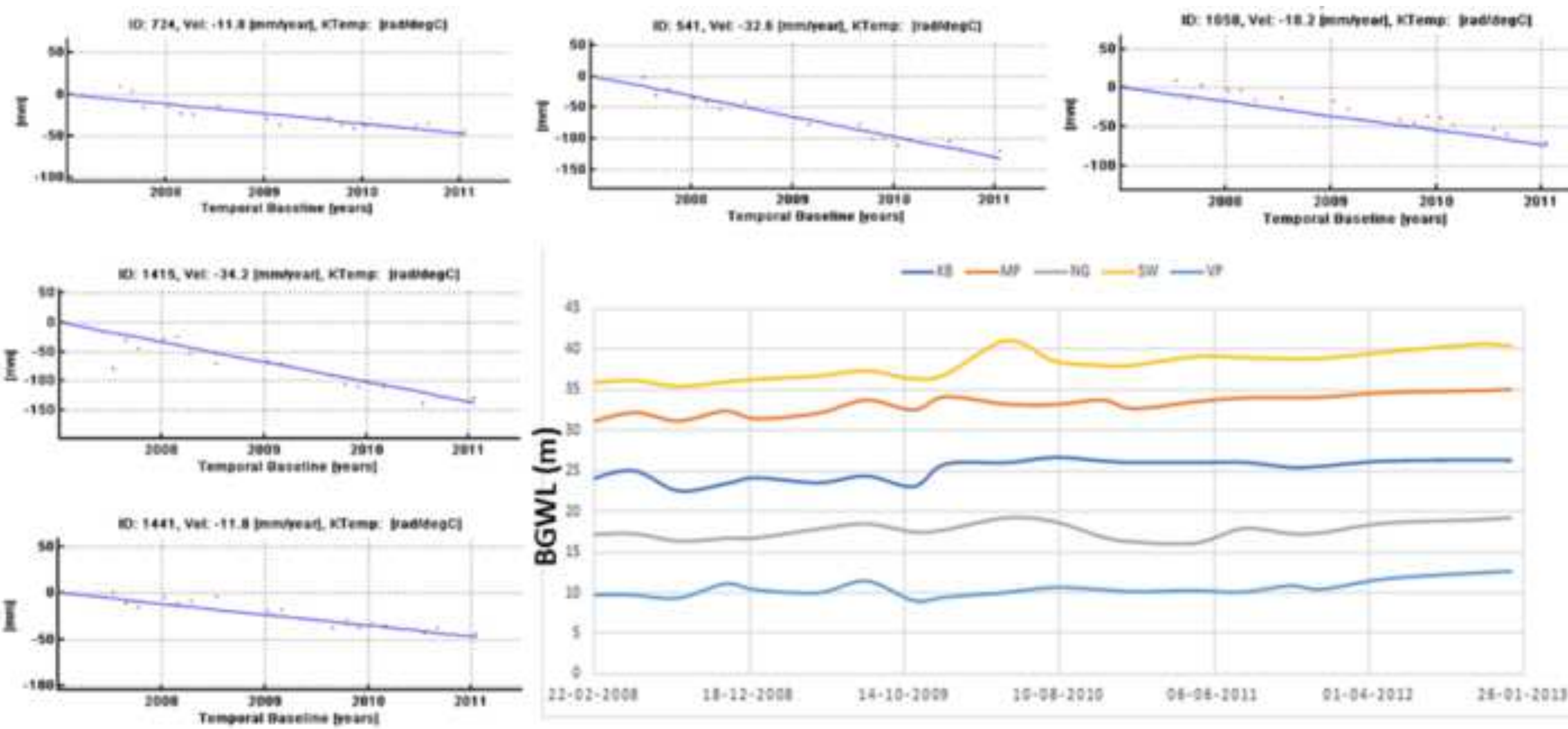
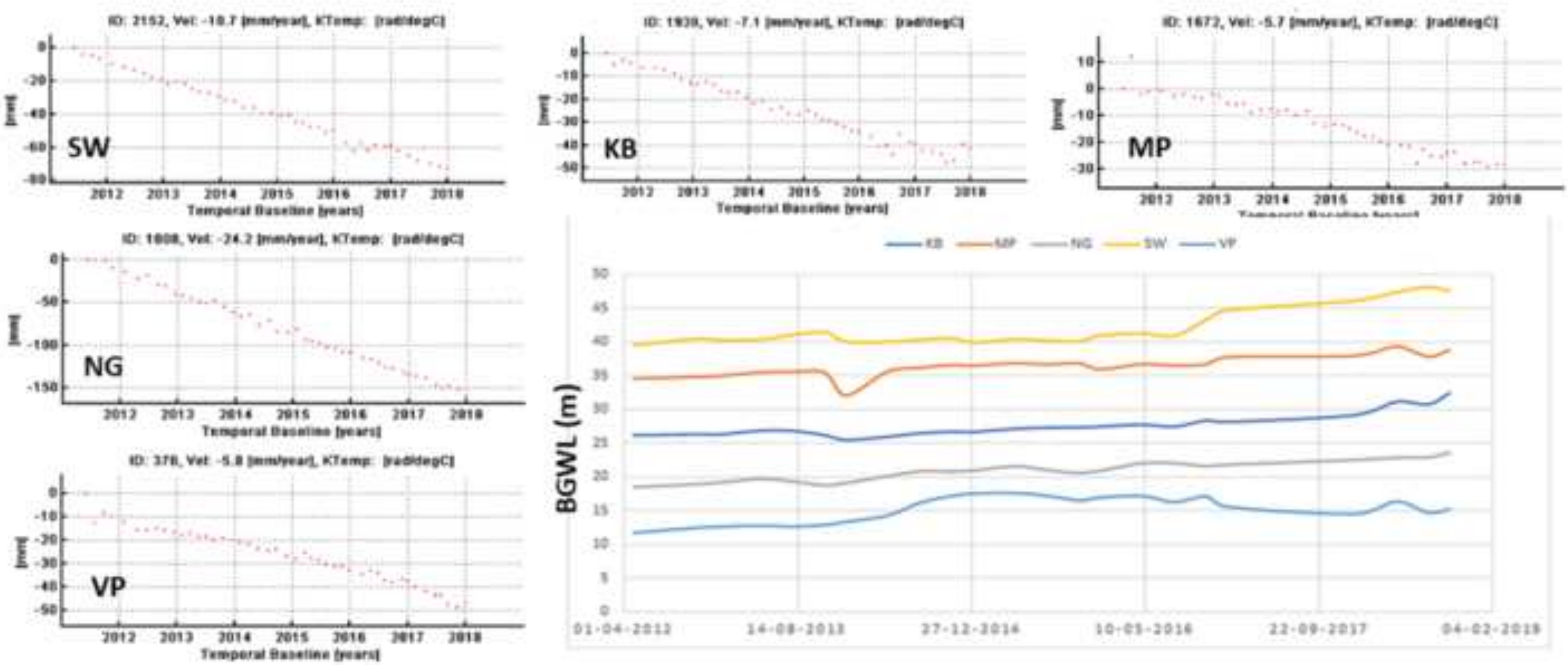


Figure-12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NG
ID: 378, Vel: -5.8 [mm/year], KTemp: [rad/degC]
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Figure-13

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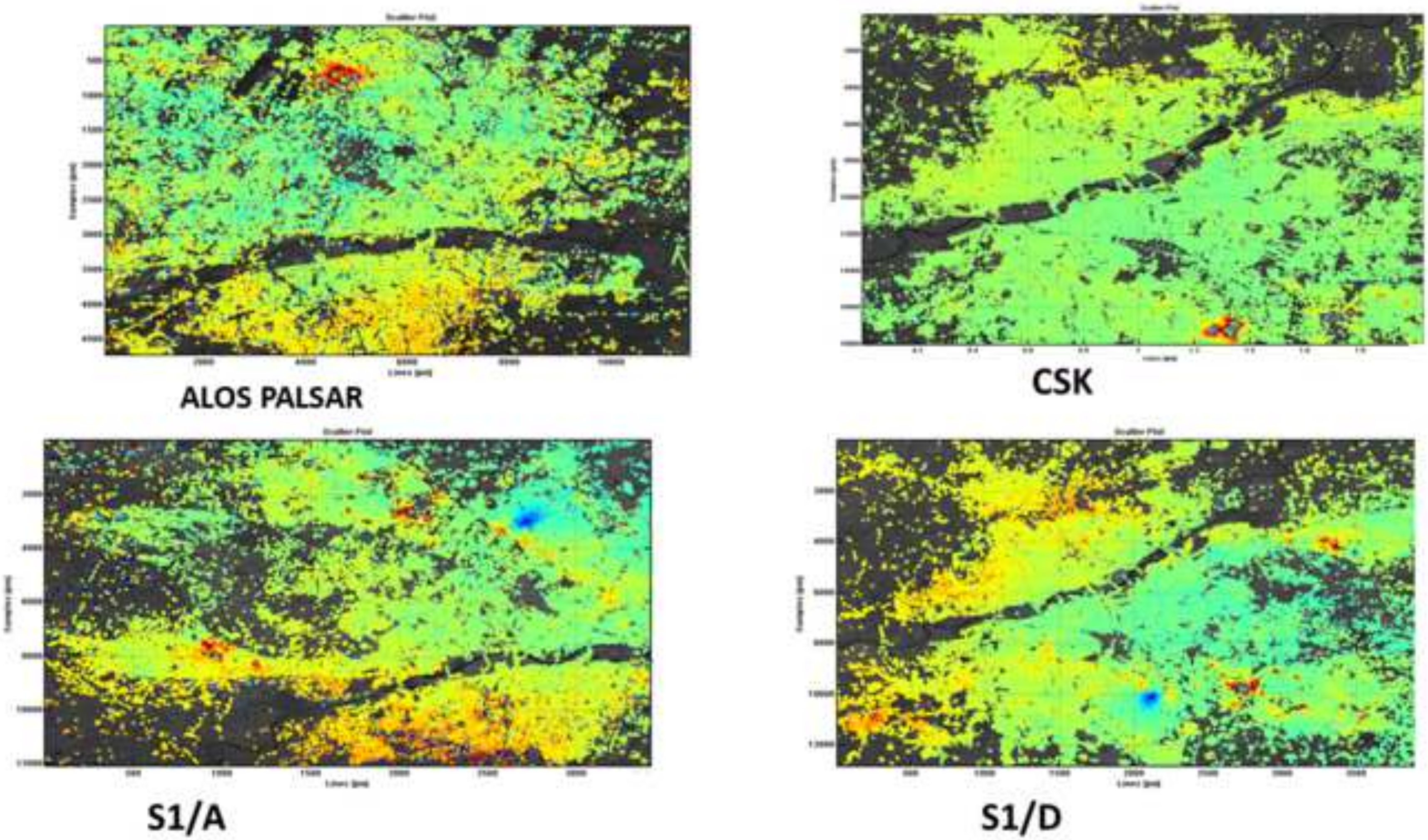

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Supplementary Material
Table_Baseline.xlsb

SN	Sensor/Band	Mode/Pol	Number of Image	Start Date	End Date	Master Image date	Average Baseline	Resolution (m)
1.	Cosmo/X-band	D/HH	45	08/06/2011	02/01/2018	23/09/2015	447	3
2.	Sentinel-1/C-band	D/VV	77	19/05/2015	23/11/2018	27/11/2016	38	10
3.	Sentinel-1/C-band	A/VV	73	18/12/2014	17/11/2018	20/10/2016	35	10
4.	ALOS-PALSAR	A/HH	18	09/01/2007	20/01/2011	04/03/2010	883	10

Details responses to reviewers

Dear Reviewer,

First of all, I express my gratitude for your help in highlighting the shortcoming in the paper. I really appreciate your effort to read the paper carefully and share your observations. During the course of the revision, I have taken all the suggestion given in review and improved the work appropriately. Answer to all the question is added below in blue. We observed that after PDF some of the figures lost the resolution. In order to address this, we have added all the figures in high resolution as supplementary data. We have also added the table in excel file showing the details of the SAR data used.

Best wishes,

Kapil Malik

Reviewer #1: General Remarks:
The article entitled "Long term land subsidence assessment in National Capital Regions of India using integrated multi-sensor interferometric time series data and custom PS-InSAR technique" was carefully reviewed. The manuscript presents the results of the land subsidence evaluations in the capital city of India. It does need to be completely revisited by authors. There are a number of syntax and grammar errors and, it also does not consist of some writing rules. I feel that these issues strongly preclude publication.

Specific objections:
* What is novelty of the paper? I could not understand it. It should be explained what the difference of your study from other similar paper is.

This paper presents the experimental result of the combining the result from the different sensor to complete the long-term monitoring. As of the sensor has the limited operational life, this work shows the way how multiple sensors can be used for long term assessment.

* Title is too long for me. It should be shorten a little.

This suggestion has been taken care.

* Keywords should be ordered alphabetically.

This suggestion has been taken care and keywords rearranged.

* The whole figures are not clear for me. Renew them by using high resolution data.

Figure has been improved and one table added to for the figure 5, as there are four graph which lost the resolution in attempt to fitting them in one figure.

In general figure lost the resolution while creating the PDF. I have attached the original figure in supplementary data.

* Reconsider how to use citation in the text. Do not write the first name of the authors. A few times, the dates were forgotten.

This has been taken care.

* Reorder the citations chronologically while referring them in the text.

This has been taken care and one missed citeation is corrected.

* Explain all synonyms when they firstly appear.

This has been taken care.

* Present the equations step by step; afterwards, explain the whole parameters in rigorous manner. Please use equation editor.

This has been taken care. Equation editor is used for adding the equation in text.

* In the text, some sentences or explanations were written repeatedly. For example, "A1

has the area extent around 2.5 x 2.5 km2 …". This is not reasonable for a professional paper.

This has been taken care.

* Some words are written frequently. For example, "use" word exists twenty times in introduction section. It is very boring for the readers.

This has been taken care.

* Title numbering is not reasonable in the text. Please correct it.

This has been taken care.

* Conclusion section is not informative for me. It should be extended and detailed more.

Now we added more details in this section.

* Rearrange references section according natural bibliography. For example, some of them do not contain title, some of them are mixed.

* In my opinion, the manuscript was not read by other authors. Please, revisit it completely.

Result:

The manuscript is vague in places and needs comments and explanations, especially in the numerical investigation part. Numerical application was performed as everybody did, i. e. there is no difference from the earlier studies. Based upon these fundamental limitations, this manuscript should not be published. Nevertheless, with a moderate amount of additional works that some of them are aforementioned, it could become a most useful contribution.

Reviewer #2: Although manuscript title is interesting, the writing lacks scholarly rigor required by Advances in Space Research. There is no clearly constructed conceptual and analytical frameworks found that can guide logically the research through. There are many serious shortcomings exist in the manuscript and hence I would recommend major revisions to this manuscript. It will provide ample time to authors revise this manuscript.

The research reported lacks demonstrated novelty in theory, methodology, and techniques. Please explicitly explain the novelty of this manuscript.

This paper presents the experimental result of the combining the result from the different sensor to complete the long-term monitoring. As of the sensor has the limited operational life, this work shows the way how multiple sensors can be used for long term assessment.

There is a good wealth of literature on the topic is available that has been largely neglected. Further, there are too many problems with English and structure.

Some more recent reference has been added and english and structure has been revisited.

Study area is poorly defined. Characteristics of the study are missing in the manuscript. Why Delhi not any other city?

Study area has been updated with new figure and more details related to geology and geomorphology.

Since Delhi is the capital region of India and has a great importance. Along with this there are several large infrastructure projects are located in study area which is worth be monitored for any possible land subsidence. This area is related to my phd work hence I have all the required data such as SAR data, GWL data etc.

It appears more like a report. Manuscript is not well connected and lacking many important information with respect to land subsidence in relation to remote sensing.

This suggestion has been taken care.

There are many sentences written in results section are actually belong to methodology. It is advised to carefully read those section and move to methodology.

This suggestion has been taken care.

Similarly, many sentences in results section should be moved to study area.

This suggestion has been taken care.

Results are not properly discussed. In overall, this manuscript needs a proper rewriting and restructuring to get published in any journal. Authors should carefully revise this manuscript and explain all the results appropriately.

Discussion section has been improved considering all the suggestion.
These all the suggestion has been added in the MS, all the question has been addressed and work improved in all the possible way.

The original figures are high resolution while after generating the PDF here it deteriorates the resolution. I have attached figures separately as supplementary data.

Reviewer #3: Dear authors, I have enjoyed reading your manuscript and its well written. However, I have follwoing question and comments.
1) Please modify title like " Use of multi-frequency SAR data to monitor land subsidence in National Capital Regions, India based on time-series PS-InSAR technique.

Yes, title has been modified and length reduced.
2) Please include quantitative data about land subsidence in abstract.

Appropriately added.
3) Please write in introduction why you choose PSInSAR instead of SBAS method as well as what is the importance of multi-frequency SAR data in land subsidence monitoring.

Explanation added.
4) Author should include more information about study area eg. population denisty, build-up area density, geology, climate, geology etc.

Study area map is improved along with more details related to geology and geomorphology added.

5) page 7 L 44: it seems, high rate of upliftment rather than subsidence. author should add some ground data either picture or other data to prove this statement otherwise author can delete.

Here in the presented map plot showing some value which is due to extrapolation. Time series in excel shows the consistent result.

6) P7 L 49-51: please provide more explanation and provide details as 9a,9b,9c....... figures otherwise its difficult to understand.

We have added the figure in supplementary material to avoid too much figure in the paper.

7) P7 L 17: author need to make a scientific discussion rather than general discussion based on previous studies.

Yes, this has been taken care in the revision.
as well as author should add validation results to prove high and low rate of subsidence

The output map is compared with ground water level data in following graph which clearly shows the reason for subsidence.

8) Conclusion: Its good if author can add some quantitative values in the conclusion and which region of the NCR has highest subsidence and why?

The output map is compared with ground water level data in following graph which clearly shows the reason for subsidence.

table1: resolution of Sentinel-1 data is 12m

We have used 10 m as output grid of the result for the all the datasets. In actual all the sensor has different range and azimuth resolution which is not mentioned.

PALSAR-1 HH polarization resolution is 12.5m, please cross check

We plotted the geocoded result at 10 for comparison purpose.
Please include max and min baseline also

Now we added the excel file as annexure which has all the information.

9) Improve study area map and description

This suggestion has been incorporated one additional map is also added.

10) figure 3 please increase resolution
Now we added the excel file as annexure which has all the information.

11) fig6. Please overlay boundary of the study area over interferogram so it's easy to compare.

We have added one figure in supplementary data for your review.
12) There is a need of more analysis and discussion about GWL data

GWL data is only used for validation while InSAR data processing result is the main objective. So limited details of the GWL data processing added.

13) please improve discussion section of manuscript.

This suggestion has been implemented.

****

ASR Editor's comments:

I have quickly reviewed this manuscript and noted that the references need some work. Many are incomplete inasmuch as they do not have all the elements required in the ASR format. Below are some general guidelines for reference citation in the "References" section at the end of your manuscript.

Quick List for Information Required in Reference Citations

1. Papers with several authors must have at least the first three authors listed before using et al. All authors can, of course, be listed.
2. Publications are much preferred over conference presentations. If a paper presented at a conference has been published in a journal (preferably) or conference proceedings, please list this publication.
3. For conference/workshop presentations (without any publication), the citation should be given a "Presentation at ......title of conference and location" Authors should be given as in a publication. If an abstract is available list the citation as an abstract and give the necessary information where a reader can find the abstract.
4. Publications must include either inclusive page numbers or paper number; the doi number is not sufficient.
5. Publications in books must have the editor(s) if appropriate, page numbers (or paper number) the name of the book, publisher and publisher's city.
6. Books require the name of the publisher and city of the publisher.
7. Journal articles require the author names, title of the paper, journal name, volume, year, and either the paper number or inclusive page numbers.
8. References with titles and/or journals in a language other than English, the English translation should be included within parenthesis.

All the above suggestions have been taken into consideration in the revised work.

Interferogram_over_basemap

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Supplementary Material
Int_over_basemap.JPG